INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.40

Requirements Trade-Off Considerations in Design Evolution

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Abstract

This paper presents approaches to compare criteria and help designers make decisions based on trade-offs between criteria. The impetus for the paper is to identify possible directions to improve/innovate a product and propose a value shell model displaying various criteria or their combination to represent the effort needed to improve the criteria. The focus is on automotive market and approaches in industry and government are differentiated. Since the effort (manpower, cost and time) needed to improve a product is not public knowledge, the paper leaves the evaluation of the approach to users.

Keywords: innovation, decision making, requirements management, value shell, trade-off studies

1. Introduction

The need to consider trade-offs in requirements to better satisfy what the user wants always confronts the engineering designers. Designers receive or capture the requirements based on various approaches and then consider all these requirements as individual objectives or criteria to design towards. Often, some of these objectives are brought together using an approach or another, such as weighted sum, and then again, trade-off between these super objectives enables the designer to identify a solution or another to apply to their design. Often, this becomes a catalogue design exercise, deciding what solution to select in order to achieve some performance objectives at some change in cost and possibly other criteria. In industry, innovation drives this process as the customer is enticed by innovations that render what they are planning to buy more at the state-of-the-art and the next best thing to have. Typically, the basic performance metrics of an artifact do not change significantly, but the innovative additions become a technology push that renders the artifact a must-have. Such a design evolution can be found in the design of vehicles. Aspects of performance or function in terms of the ability of the vehicle to take a person from one location to another are not even questioned by the buyers and are assumed to be met by any vehicle on the market. Nevertheless, hybrid and electric vehicles have somewhat changed the user requirements, though buyers may usually be interested in such a technology more for its impact on the environment than for the vehicle performance. The potential customers may focus on fuel consumption, safety, and convenience, but also, added features such as blind spot sensors (BLISS), connection to service centres, automated braking, or line departure warning availability. Advertisers focus on these additional "options", based on perceived or proven historical data such as safety of Volvo or Subaru cars, or on some apparently novel affordances such as those available in the GMC Sierra's Six-Way tailgate feature. Every added option to the vehicle increases its cost; and some vehicle manufacturers have come up with standard packages for fleets of vehicles to reduce the variability of added features.

What happens however in the case of, for instance, fleet acquisition by the Department of Defense for a specific mission profile? The requirements for such a specific type of vehicle ideally include: the fastest, safest, strongest, cheapest, most lethal, most reliable, most energy efficient, and most terrain versatile vehicle, among others, they can acquire.

Wilfred Pareto (Pareto, 1906) at the turn of the last century came up with the concept of Pareto optimality, describing how there is no "ideal" solution that maximizes all criteria, but instead there are multiple solutions that are Pareto optimal, meaning that improving one or more criteria will lead to the deterioration of one or more other criteria. Thus, how do designers and engineers make decisions when considering such trade-offs? Which criterion should they focus on? In an attempt to shed light on these challenges, this paper investigates the concept of trade-offs in engineering design and asks if a graphical illustration of criteria trade-offs considering effort required to improve them can help decision making, and furthermore, if it can help identify when and what to innovate or when new technologies may have to be introduced.

The paper is structured as follows: Section 2 describes what innovations typically target in mechanical engineering design, which can be new functionalities or new affordances. Section 3 summarizes relevant literature and the consideration of criteria to decide on innovations. It describes what are typical engineering innovations, whether they are function or affordance based and shows some examples from automotive industries. Section 4 describes decision metrics and attempts to characterize the "value" of a design and the "effort" needed to improve on such a design. It then expands on some examples from the defense industry focusing on vehicles. Section 5 describes a proposed graphical approach to help designers decide on what and when to innovate. Lastly, Section 6 concludes the paper and challenges the readers to think of the proposed approach and possibly implement it, if possible, to identify its potentials and shortcomings.

2. Relationship between innovation and affordances

Innovation, more specifically product innovation, is a hot topic in the current economic climate. Companies and governments know that the consumer society demands innovative products that offer always new and improved affordances and possibly functionalities to their customers. Most Universities now offer courses on innovation management, entrepreneurship, design, and manufacturing, and the advent of 3D printing and simultaneous leaps in computer power and novel materials (e.g., Big Data, Deep Learning, autonomy, nano- and meta- materials) usher a new era of design and manufacture. Given this situation, how can we help government and industries decide on managing risk, on which technology to pursue and on when should innovation be implemented?

Before expanding on the topic, the aspects of affordances and functions as used in this paper are clarified since the engineering design community has not yet fully adopted clear definitions of these concepts.

Function is a transformation. It takes an input and produces an output, similar to a mathematical function: $y = f(x)$, and can be described in a flow diagram. Function is not size- or shape-dependent. Transforming fuel or energy into torque for instance, is a function that can be accomplished by different solutions such as a fuel-based engine or a diesel engine, or an electric motor. Their size is not defined by the function.

Affordance is a more descriptive term indicating what a user may infer can be done with an artifact. Affordance is size and shape dependent and is not described as a transformation. It can capture user interaction issues, and is often related to visual perception, especially in the ecological psychology field where it emerged from (Gibson, 1979). Function, because of its structure, can only describe a simple or complicated system, whereas affordances can help describe the complexity of a system (Pahl and Beitz, 1996; Otto and Wood, 2001; Maier and Fadel, 2001, 2009, 2009b). The functions of an artifact are limited as opposed to the affordances which can be unlimited, although designers focus on what they want the users to infer they can do when using the product. A pen for instance affords writing but could afford stabbing or throwing even though it is intended to be used as a writing tool. A drinking glass is designed to hold a certain amount of liquid, but some glasses afford holding in such a way that the liquid is warmed by the heat of the hand holding it (cognac glass for instance) or holding it by a handle or a stem such that the liquid is not affected by hand heat (a beer mug or a champagne or wine glass). Another example is the steel "bird cage" armor put around army vehicles to protect them from rocket propelled grenades (RPGs). Although heavy and lightweight options are available, the steel version could also be used as a ram. Note that according to these definitions, most of the "innovations" in vehicles are improvements in affordances for the user. There is no optimum; affordances can always be added, but certainly at some cost to the user.

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Should a company decide on a new product launch, whether innovating or redesigning, the aspects of expected profit, strategic positioning, and expectation to differentiate the company from its competitors are criteria not usually considered by engineering designers, but rather by company executives who make decisions. To make informed decisions, they need to have some idea of both the expected response of the consumer and the cost of the innovation. Should the innovation affect the artifact performance or function, virtual and physical simulations and tests are conducted to determine the possible effects of the innovation on the artifact's performance or function. User surveys are conducted, and decisions are taken based on the results. For the Department of Defense (DOD), the increase in capabilities of the soldiers and their safety are the driving factors when considering vehicle designs. The cost to achieve such improvements eventually limits what can be done at the current state of the art. "What are the limitations that need to be overcome?" and "when should one invest in identifying innovative solutions?" are questions this paper attempts to address.

Since our focus is on the mechanical or mechatronic design, we will position the research questions based on typical mechanical design processes: What can one innovate in mechanical design? Engineers could select a new working principle to accomplish a specific subfunction or set of subfunctions, they can select a new material which may provide advantages over previous ones but that may be more costly and more difficult to manufacture yet provides better performance (e.g., composites, nanostructures, metamaterials), or select new manufacturing paradigms and processes. Our interest is in developing a process that can help industries and program managers decide when it may be the time to move toward a new technology, which technology it should be, and possibly, what risk may be associated with adopting that change.

3. Literature review and examples

3.1. Innovation and Lean Product Development

Much of the literature on innovation relates to the ideation process and appropriate criteria to use when selecting what innovation to pursue. Paul Wright of Invetech (2015) defines innovation as "the successful exploitation of new ideas to increase customer value or create wealth for a company." He defines three levels of innovation according to the degree of newness and value added in which an incremental innovation adds little value but presents some newness while a radical innovation adds a lot of value and is totally innovative.

Few researchers have focused on how opportune or critical the time is for a company to develop an idea, when a novel idea should be incorporated in a design or what the risk is associated with incorporating the novel idea. Lean Innovation authors (Ward, 2007; Cooper, 2011) and many others laud the importance of innovation, and how companies should re-think their approaches to innovation to be successful in the long term. Most companies today select ideas based on some evaluation criteria such as: to what degree are existing customer needs satisfied? What is the risk associated with a new idea? and, what is its cost? (Messerle et al., 2012, 2013; Breiing and Knosola, 1997; Guttierrez, 2011). These authors consider the case where the company has decided to innovate a specific aspect of a product and is attempting to come up with a methodology and evaluation criteria to select the better and less risky ideas. Other proposed evaluation criteria can be found in (Hart et al., 2003, Tzokas et al., 2004, Carbonell-Foulquié et al., 2004, von Ahsen et al., 2010, Stern and Jaberg, 2010, Cooper, 2011, Hauschildt and Salomo, 2011). To consider multiple criteria, usually a Simple Additive Weighting (SAW) method or an Analytical Hierarchy Process (AHP) approach is used to decide on a solution. Trade-off curves are also often used to support decision making and show the relationship between two or more parameters that relate design decisions to the desires of customers for instance (Ward, 2007).

But how should the company decide what aspect of the design to innovate? Yannou et al., 2013; Stevanovic et al. (2013), investigated various criteria to identify some of the most appropriate innovations. They identify 9 criteria, more business- than engineering-oriented, to assess the need for invention based on effort, value, and risk.

We can therefore see multiple efforts at identifying ideas, evaluating them, and deciding on criteria and methods to combine them. Yet, as most products evolve, is there another way to help the decision maker make the right decision about where to focus effort and innovation? What criteria are those decisions based on? These aspects are the focus of the next section.

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3.2. How and when companies decide what innovation to introduce

In the case of automobiles, novel designs are proposed every year to support the consumer society's thirst for new products. Often, slight modifications to the vehicle are implemented, and the life of a vehicle series may last between five years and a lifetime.

The BMW X5, for instance, was developed over many years and saw its first model on the market in 1999 (Caradvice, 2019). That model, the E53 BMW X5, remained more or less fixed in design over its 7 years of availability (1999-2006), seeing minor aesthetic improvements such as modifying the head- and taillights and the wheels. A different engine was also added as an option in 2003. The E70 BMW X5 (2005-2013) was a slightly longer and wider car, it allowed a possible third-row seating, and its interior was completely redone. The vehicle also had active steering and roll stabilization, a head-up display, keyless entry, and four-zone climate control. The F15 BMW X5 (2014-2018) was again slightly longer and wider, with a wheelbase identical to the previous generation. Interior modification included a freestanding 10.2 inch screen in the center console and the latest iDrive and head-up display technology. The rear end was also modified. The current generation G05 BMW X5 (2019-) incorporated semi-autonomous technology and again saw changes in the rear end, on the front grille, and a longer wheelbase.

Considering this evolution, what was the significant innovation? Aside from the semi-autonomous technology implemented in the latest series, there is no apparent functional improvement due to a technology change.

Another vehicle that remained very much the same over its lifetime is the Volkswagen Beetle, first released in 1938. In 1946, the factory was put under British control but continued to produce the same vehicle. By 1956, more than one million had been sold. It is only in 1971 that the super Beetle was released with a front suspension and added trunk space. Over 15 million Beetles had been sold by then. In 1998, the New Beetle was introduced based on the Volkswagen Golf platform with a swap of the engine from the rear of the original Beetle to the front. In 2018, Volkswagen finally announced the end of the line for the Beetle but also presented two convertible models. In the VW case, the innovations do not seem visible before the new Beetle, yet the addition of safety systems like seat belts and airbags mandated by law became common in most vehicles.

Automotive manufacturers decide, therefore, on the life of a vehicle series and base their innovations on marketing and business concerns. Societal changes also impact vehicle design. The energy crisis in the early '70s pushed the development of more energy-efficient engines, alternative fuel sources such as hydrogen and methane, and eventually, electric and hybrid vehicles. Today, the ability to use in-hub motors and regenerate energy when braking or coasting is becoming a natural evolution of vehicles. Fully electric vehicles have certainly penetrated the market in the last few years, but is the electric grid and electric supply ready for such a drastic change in society? Economic, societal, sustainability issues and availability of energy in the form of fuel or alternative efficient resources will continue to drive vehicle innovations in the next few years. Autonomous driving will probably become more the norm on highways, which will increase the number of vehicles, reduce the space between vehicles, and result in fewer crashes.

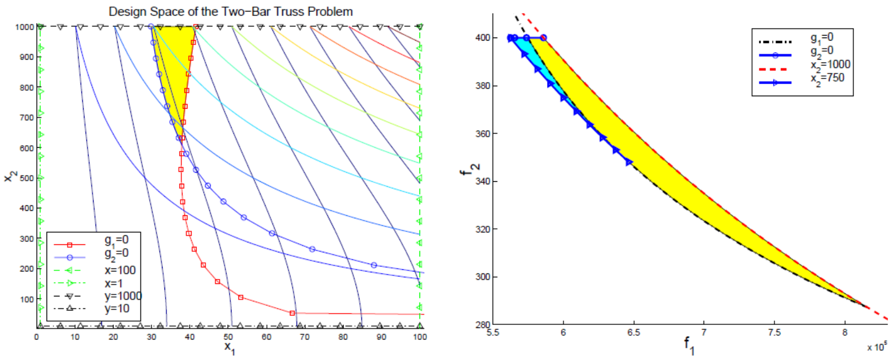
There is still a need, however, to attempt to identify a methodology to help decision-makers decide when to invest in a novel technology and eventually introduce it to the public.

4. Decision metrics

4.1. The “value” of a design

The representation of the “Value” of a design in the design space is a difficult concept to visualize. The design space is defined by the allowable range of variation of all the independent design variables that describe an artifact. In the field of optimization, the design or decision space can be represented in a coordinate system representing these design variables. Alternatively, if the coordinate system represents the metrics or objectives of a design, and the space is bounded by constraints, it is referred to as objective space. Still the question remains: “How do we assess the value of a design?” If multiple solutions are represented in a design or decision space, it is impossible to assess a value to each design. If they are displayed in an objectives space, how each solution satisfies an objective is more apparent, however, since there are multiple objectives or criteria, assessing a value is difficult.

The field of multi-criteria optimization describes the Pareto front, or the set of solutions optimal to some combination of objectives, where improving one objective necessarily results in the degradation of at least one other objective. Thus, designs never reach what is referred to as the Ideal Final Result (as defined in TRIZ) [Altshuller et al., 1999] or the Ideal Point as defined in optimization: the design that is best with respect to all the objectives or criteria simultaneously.
Objective spaces are represented for two or three objectives at most because of the human's ability to visualize two- or three-dimensional spaces. Representing higher dimensional spaces is not obvious, although spider diagrams have been used to this effect. In Figure 1, the classical two-bar truss problem [Chen, 1995], often used in structural optimization as a benchmark problem, is illustrated in the design space as well as the objective space. The problem consists of two pipes with average diameter d and thickness T connected in the form of a triangle, fixed at both bottom sides of the pipes and loaded at the top point where the pipes are joined. The bi-objective problem is to reduce the weight of the structure (objective f1), as well as the stress (objective f2) subject to constraints on allowable and buckling stresses. The yellow area is the allowable design space. The points bounding the design space on the bottom left of the objective space graph are the Pareto points forming a curve. Moving along that curve shows the trade-off between objectives f1 and f2.



(a) Design space (b) Objective space

Figure 1. Design space of two bar truss problem [Li, 1999]

In Figure 2, a star diagram with multiple criteria describes the "value" of two specific designs considering multiple objectives. In this particular representation, the objectives or criteria are arbitrarily described in different directions, and the segmented lines joining the values of the various criteria represent different solutions. The angles between the criteria are constant and depend on the number of criteria considered. Unlike the coordinate system in Figure 1, in this graph, the trade-off between the objectives or criteria is not visible. The graph enables only the comparison between multiple solutions with respect to the multiple criteria. The relationships between the criteria are not considered, and each is considered individually.

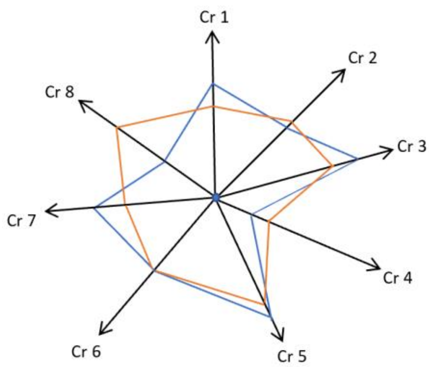


Figure 2. Star diagram representing two solutions (red and blue) with multiple criteria

From Figure 2, the "value" of a design could be related to the surface defined by the lines joining the various criteria values. This however does not consider the different weights that could be attributed

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to individual criteria since some criteria may be deemed to be more important than others. Also, in this example, all criteria are assumed to be increasing functions, meaning that the distance from the center is related to how the design performs on that specific aspect. Note that if the criteria scales are different, and if the value preference on individual criterion is not linear, tools such as utility theory (Hazelrigg, 2012) could be used to represent all criteria using utils (a mapping between the minimum and the maximum of a criterion to a nonlinear utility function between 0 and 1 obtained by asking the customer at a certain probability, p, corresponding to a util, what certain value of the criterion is equivalent to the probability p s/he would accept the criterion at its maximum and $(1-p)$ at its minimum. For instance, for a probability of 50% or 0.5 util, would one accept a certain salary of \$100k or a probability of $p = 50\%$ s/he will be offered \$150K and $(1-p)$ \$50K). The probability p is the util and the value where the two choices are considered equal the point on the graph to create the mapping). Furthermore, weights could be used to identify an overall value when multiple criteria are considered. This is however a tedious exercise, especially when attempting to decide how to modify a design to better respond to the users wishes, and more critically, when attempting to decide whether a new technology needs to be considered to gain market or functional advantage.

4.2. Directions of product improvement, DfX

Design for X was coined in the 1990's after several researchers focused on specific aspects of a product such as its ease of assembly (Design for Assembly or DfA), ease of manufacture (Design for Manufacturability or DfM), in addition to design for quality, design for reliability, design for ergonomics, and so forth. Each DfX design team focuses on some aspect of the design or eventual production to improve their product. How can one decide on the direction of improvement at some stage of the design? One could extend the star diagram of figure 3 to show the trade-off between various criteria, however, it becomes very difficult to assess the magnitude of that trade-off.

Ouellette [1992], attempted to identify criteria that were similar when considering the design of an automobile, and which were clearly in conflict with each other (increasing one necessarily decreases the other). He generated three criteria that seem to always be antagonistic, namely Please, Protect, and *Icost*. "Please" represents the aspects of performance, appearance, and ease of use, but can also refer to the ease of maintenance for mechanics who need to maintain the vehicle. It gathers several criteria represented on the star diagram, but which do not impact each other negatively. The "Protect" metric is related to safety for the user, the environment, for other users. The "Icost" metric is the inverse of cost in order to have an increasing scale when reducing the cost. Cost is defined by Ouellette as related to the cost of a component and manufacture plus the material cost.

It can be said that these three metrics are balanced because typically a design cannot be improved in one of these areas without negatively affecting at least one other. This is because the measures are not orthogonal, as shown in Figure 3.

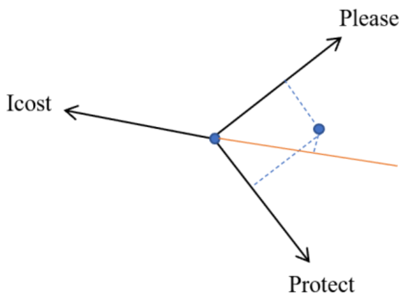

Figure 3. Metrics

The angles between the three axes are not fixed but will change depending on the particular design. Since the metrics are not orthogonal, some goals of two metrics may be coincident, such as an improvement in serviceability which will increase both please and protect. We can therefore see that this approach attempts to capture the relationship between the metrics, and instead of showing a design via a spider diagram, as in Figure 2, here a design is a point on this diagram, and the values of the criteria are obtained by projecting the point onto the axes.

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What is the center point in this figure? It could represent the current artifact, and improvements to it can be carried out by moving in any direction, reducing the cost (increasing the Icost) for instance, or increasing safety, performance, functionality, adding affordances, or improving its aesthetics. Certainly, a combination of these can be also pursued, and the new design would be represented by another point on that plane as illustrated in the figure.

4.3. Example: DOD vehicle evolution

Instead of the please, protect and Icost metrics, in order to be more aligned with the DOD's needs, one could consider Payload, Mobility and Protection metrics as the three trade-off values described in the paper by Dasch and Gorsich, 2017. In this particular example shown in Figure 4, three tactical vehicles from the Department of Defense showing the progressive generation from the HMMWV to the MRAP to the JLTV are compared. The spider graph approach is used, and the relationship between the three axes is not considered. If one measures the relative measures on the three axes, Table 1 can be generated. Normalizing the mobility measure, Table 2 is produced. This shows that the MRAP lost mobility when compared with the HMMWV, but the JLTV went back to the mobility performance of the HMMWV. The protection of both the MRAP and JLTV are significantly improved over that of the original HMMWV, and the payload capability of the three series is similar. Note that in the paper by Dasch and Gorsich, 2017, they mention that the many armor upgrades of the HMMWV more than doubled the weight of the original vehicle at the expense of mobility and payload capacity.

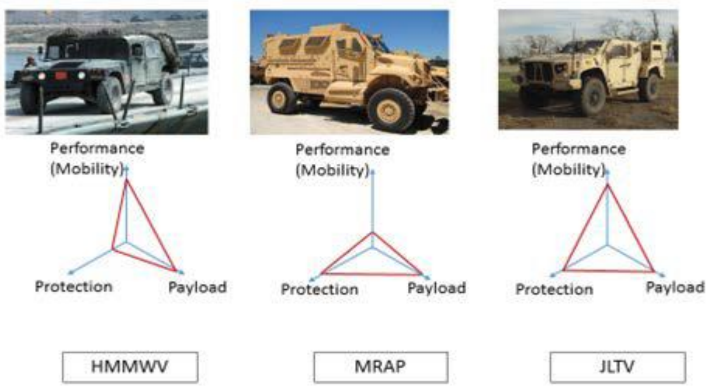

Figure 4. The "Iron Triangle" (Dasch and Gorsich, 2017)

Table 1. Comparison of relative performance of three DOD vehicles based on Figure 5.

	HMMWV	MRAP	JLTV
Protection	1	4	3.5
Mobility	1	0.25	1
Payload	1	1	1

Table 2. Normalized relative performances of the three DOD vehicles

	HMMWV	MRAP	JLTV
Protection	1	4	3.5
Mobility	4	1	4
Payload	1	1	1

This iron triangle unfortunately does not provide us with the trade-off cost, and the implementation of the evolution of the vehicles on the graph of Figure 4 is not possible without additional information. One can however see that the protection improvement was essential from the HMMWV forward. With the MRAP, the protection improvement came at the expense of mobility since the resulting increase in weight affected that metric. The JLTV was able to maintain the nearly same level of protection as the MRAP but was able to address the mobility issue more effectively than for the MRAP, one nearly equivalent to that of the HMMWV. Note that the MRAPs were rushed through

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the process to protect the soldiers and did not go through the normal acquisition process. This information may be critical to assess where to innovate effectively.
Using information from Green and Stewart (2005), and since effort information to modify the vehicles is not available, the display of the progressive models of the HMMWV and subsequent vehicles on the flat version of the value shell was attempted. Note that the impact of an increase in one metric on the other metrics cannot be assessed from the information available, and therefore, the angle between the metrics is difficult to define. However, one can assume that any increase in protection through added heavy armor negatively impacts mobility and also payload. However, an increase in mobility has some correlation with the ability to protect the soldiers in the vehicle, and therefore some of these criteria are not necessarily independent. If the three axes are displayed for illustrative purposes at equal angles from each other, one could attempt to see the progression of the vehicle versions. Note that various models of the vehicles were commissioned for very different mission profiles. The initial HMMWV was designed for 15 different configurations, from cargo/troop carrier to shelter, to ambulance, to missile carrier, armament carrier, and all of these with or without winch, and some with or without armor. The A1 configuration had similar mission profiles to those who became the A0 configuration, but because of handling problems towing howitzers, they had larger reinforced rear bumpers and other minor changes. The A2 series saw a significant reduction in vehicle variants from 15 to 9, merging several missions in vehicles that were able to handle more flexibility. For instance, the armament and tow versions were merged, and the mini-ambulance version was eliminated.
A rough evaluation of the cargo/troop carrier HMMWV evolution is as follows:

A0	Basic M998 HMMWV
HHV A0	M1097, Increase in payload and mobility
A1	M998A1 Same as HHV A0 but more standardization
A2	M1097A2 Increase in mobility (engine, Transmission, Central Tire Inflation System CTIS), increase in payload
ECV/ECH	Increased payload, larger engine therefore increased mobility
M1151	Increased protection, increased payload
A3	Increased mobility – Not pursued
HYBRID	Ability to have smaller engine, and electrical production for alternative Uses- Not pursued

Since the criteria are not necessarily contradictory, the first attempt is to place the various versions on a star diagram as per Figure 2 resulting in Figure 5.

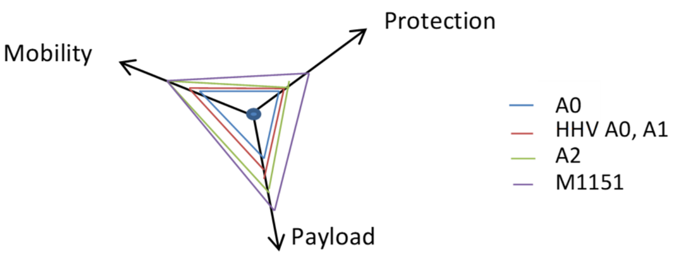

Figure 5. Star diagram HMMWV evolution

This graph, as mentioned earlier, only shows that there is a desire to increase all criteria, but no trade-off is apparent, nor is the effort needed to improve any criterion or combination of criteria.
It is worth noticing that the various versions of the HMMWV increased both payload and mobility, two criteria that should be conflicting. Increasing the weight renders the vehicle less mobile in general unless the designs of the engine, suspension and frame enable the vehicle to carry more weight while becoming more mobile, which is what the manufacturers addressed. Also, protection should be conflicting with payload since the addition of armor adds weight, and this is at the expense of the ability to increase the payload. However, the M1151 increased all three criteria.

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4.4. Effort needed for improving or innovating a product

Assessing the effort needed to improve some criteria is difficult for academic researchers. A design class could be used to attempt to measure the effort needed by students to improve on a former design, and that effort could be assessed in terms of the number of student hours expanded on the project, for instance. In industry, managers have a better handle on effort expanded. They know who the individuals are that work on the project, what their salaries are, how many hours are spent on specific tasks, and what budget they have to spend on developing, testing, measuring, and producing innovation. They know the space and overhead requirements and the cost of consultants or partners. The effort metric could then be obtained by some combination of these quantities.

It takes effort to change a design. This is primarily effort on the part of the design team which includes engineers and manufacturing personnel. To add more value to the design, effort must be expended. Effort is manpower, money, and time. This leads to the view shown in Figure 5 below, where the function effort is equal to some function of Value or E(v) and is any increasing function.

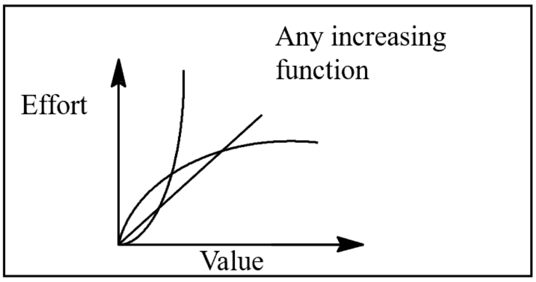

Figure 6. Effort as a function of value

In the real world, there is a diminishing return for the effort that is put in. With some effort, the design can be improved; but as more improvement is sought, additional effort is expended, and it becomes increasingly difficult to improve some aspects of the design. This means that the equation E(v) or Effort as a function of Value, should be increasing slowly at first, but become steeper later. A simple equation which fits these criteria is a parabola; another is an exponential. In the case of the parabola, the equation is:

$$E(v) = kv^2$$

where k is the constant that determines how open the parabola is.

If it is possible to identify the additional effort expended to move from one generation to the next in a design, it may be possible to fit a curve and represent that increase in effort as a function of an increase in value.

5. Proposed value shell model

As described earlier in the thesis of Ouellette (1992), a vehicle design was defined by the customer metrics of Please, Protect, and Icost. These three metrics could be used to determine the value of a design relative to other designs by placing a point on the graph representing the change in these metrics. But the change in these metrics requires effort. In this light, applying these metrics in the two−dimensional scheme is difficult; the design team will want to consider all three metrics and effort simultaneously. This leads to the design shell or bowl, as depicted in Figure 6.

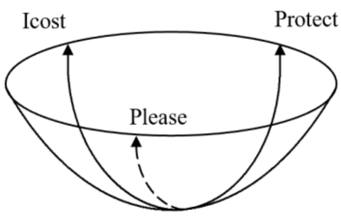

Figure 7. The Design Shell [Kirschman, 1996]

This shell or bowl is defined by the three metrics as different parabolas on the surface. This shell is obviously not necessarily round since the parabolas will not have the same constants. In this scheme,

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the bottom of the bowl (minimum effort point) represents the current design. Effort must be expended to increase the value of that design. How much effort depends on which value the design team wishes to increase. This is similar to the energy states of an electron. To increase the orbit of an electron, energy is expended. Similarly, to increase the value of the design, human energy and money (effort) is expended. There is a tendency for an increase in one of the metrics to cause a decrease in at least one of the others. But, as a particular metric is increased further and further, it requires more and more effort on the part of the design team to accomplish the goal. When the effort required for an improvement is too great, the best way to improve customer satisfaction is by changing the technology.

At no time is the exact size of the shell known, only the slopes in different directions may be able to be estimated by the design team. As technology matures, the slopes of the shell become steeper, making improvements more difficult to design. Even though these improvements still increase the value of the product, the design effort may add too much cost to the product for it to be economically feasible for the company.

Figure 8 equates the opening of the value shell with the flexibility of the technology.

A large, shallow shell has lots of room for improvement in all areas, which is evidence of very flexible technology. A steeper shell or bowl, however, has very little room for improvement and a large expenditure of effort is required to improve the product. This technology dies much more quickly as it is surpassed. Often, this steeper shell is indicative of mature technology, one that is well understood but has little remaining room for improvement. Also, since the shell or bowl is not round, some aspects of the technology may be more challenging to improve than others, and the bowl would be narrower and steeper in those difficult to improve directions.

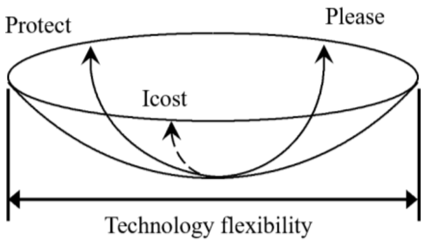

Figure 8. Flexibility Measured on Design Shell

Considering the DOD vehicles, one could consider the three metrics of interest and attempt to place the various versions of the vehicles progressively designed on a design shell. Figure 9 shows the bowl as adapted to the three DOD metrics. Increasing protection negatively impacts payload and mobility. Improving on any of the criteria requires effort and progressive models may be placed at various locations on the shell.

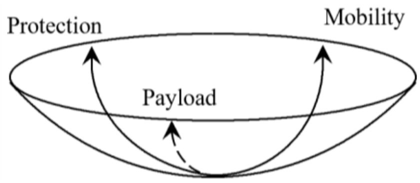

Figure 9. Design Shell for DOD vehicles

Furthermore, as is shown in Figure 10, the jump from one technology to another does not necessarily mean that all three metrics will improve. There may be overlap in the bowls, and the value of the product may remain the same or even decrease with a technological jump. However, the new technology should provide more room for improvement in all directions, allowing the designer to improve the product beyond the value in the previous technology.

Designs can only go up a shell. If a design is changed, it becomes the origin of a new shell. It is possible for the design to go back to the original metric values, but only at a higher effort. Effort, like entropy, always increases.

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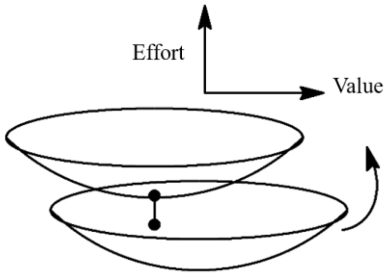

Figure 10. Changing Design Shells via Technology Change

Based on the study above, the idea of the design shell is difficult if not impossible to generate if not performed in a company with access to all the required information. So, what can the DOD do to identify where to improve their vehicles or where to increase specific requirements? Maybe by considering each criterion independently and generating the value effort curve for that particular criterion or combination of criteria. The slope of the curve should be an indicator of the difficulty of improving that or those criteria, and too steep a curve should indicate the need to come up with alternative solutions or technologies to address the problem.

Taking the example of the protection criterion, one could come up with a curve that shows the effort needed to increase protection. Armor plating can be added to the body of the vehicle, armor glass can be added, the windows reduced in size, this will be at the expense of mobility very probably, and this has been done at some cost and effort. Next, undercarriage armor for IEDs can be added, this reduces the ground clearance and adds weight. Therefore, both mobility and payload are affected. This has also been done. Alternative materials for armor plating could be developed at significant cost and effort to replace the heavy Kevlar, but if they are lighter, they would have a much smaller effect on payload for instance. This reasoning is true for material improvements to armor that have been very incremental and at the cost of excessive weight, However, autonomy for instance, can greatly improve survivability without the weight impacts. The DOD refers to these new technology improvements as Active Protective Systems (APS) and would be represented by a leap in the graph shown earlier since this is a "new technology."

6. Conclusions

In this paper, we attempted to describe various ways trade-offs are considered in engineering design with a specific focus on automotive and Department of Defense vehicles design. The paper asks how designers and engineers make decisions when considering such trade-offs, which criterion they should focus on? and whether a graphical illustration of criteria trade-offs considering effort expanded can help decision making and help identify when and what to innovate or when new technologies may have to be introduced. A proposed approach to graphically display trade-offs and help designers and contracting personnel make decisions is discussed but unfortunately, not implemented since the information required to assess effort needed is proprietary and only available withina company. Additional work is needed to explore the ideas presented and to assess the relevance of the approach. It is hoped that researchers will build on the ideas proposed to further the work and establish usable methods.

Acknowledgement

This work was supported by the Virtual Prototyping Ground Systems (VIPR-GS) Center at Clemson University and the Automotive Research Center (ARC), a US Army Center of Excellence for modeling and simulation of ground vehicles, under Cooperative Agreement W56HZV-19-2-0001 with the US Army DEVCOM Ground Vehicle Systems Center (GVSC). All opinions, conclusions and findings wherein are those of the authors and may not be those of the affiliated institutions. Distribution A. Approved for public release, distribution unlimited. (OPSEC #5947).

References

Altshuller, G.S., Shulyak, L., Rodman, S. (1999) The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity, Worcester, MA, Technical Innovation Center Inc.

Anderson, D. M. and B. J. Pine, II (1997). Agile Product Development for Mass Customization. Chicago, Irwin publishers

https://doi.org/10.1017/pds.2022.40 Published online by Cambridge University Press

Breiing, A. and Knosola, R. (1997) Bewerten technischer Systeme. Berlin: Springer.
Caradvice, 2019, https://caradvice.com.au/655950/bmw-x5-through-the-generations/
Carbonell-Foulquié, P., Munuera-Alemán, J. and Rodríguez-Escudero, A. (2004) Criteria employed for go/no-go decisions when developing successful highly innovative products. Industrial Marketing Management, Vol. 33, No. 4, pp. 307-316.
Chen, W., A Robust Conceptual Exploration Method for Configuring Complex Systems", Ph.D. thesis, Georgia Institute of Technology, August 1995
Cooper, R. (2011) Winning at new products. New York: Basic Books.
Dasch, JM, Gorsich, DJ (2017) The role of R&D in an Acquisition Program. J. Def. Manag. 7:170. https://dx.doi.org/10.4172/2167-0374.1000170
Gibson, J. J., 1979, "The theory of affordances," The ecological approach to visual perception, Lawrence Erlbaum Associates, Inc., Hillsdale, NJ.
Green, M., and Stewart, G, 2005, HUMVEE at War; Zenith Press
Gutiérrez, E. (2011) When sensemaking meets resource allocation: an exploratory study of ambiguous ideas in project portfolio management, International Conference on Engineering Design, ICED11, Copenhagen, August 15 - 18, Copenhagen: The Design Society and the Technical University of Denmark, pp. 373-382
Hart, S., Hultink, E., Tzokas, N. and Commandeur, H. (2003) Industrial Companies' Evaluation Criteria in New Product Development Gates. Journal of Product Innovation Management, Vol. 20, No. 1, pp. 22-36.
Hauschildt, J. and Salomo, S. (2011) Innovationsmanagement. München: Vahlen
Hazelrigg, G. (2012) Fundamentals of Decision Making: For Engineering Design, Neils Corp.
Kirschmann, C., "Using Functions and Metrics at the Conceptual Stage of Mechanical Design", Ph.D. thesis, Clemson University, August 1996
Li, Y., "approximating The Pareto Set of Convex Bi-Criteria Optimization Problems to Aid Decision Making in Design", Ph.D. Thesis, Clemson University, May 1999.
Maier, J. R. A., and Fadel, G. M., 2001, "Affordance: The fundamental concept in engineering design," ASME IDETC/CIE 2001, pp. 1–10.
Maier, J. R. A., and Fadel, G. M., 2009, "Affordance-based design methods for innovative design, redesign and reverse engineering," Res. Eng. Des., 20(4), pp. 225–239.
Maier, J. R. A., and Fadel, G. M., 2009b, "Affordance based design: a relational theory for design," Res. Eng. Des., 20(1), pp. 13–27.
Messerle, M., Binz, H., et al., "Existing problems of idea evaluations and possible areas of improvement", In: Proceedings of International Design Conference - Design 2012, Dubrovnik, Croatia, 2012.
Messerle, M., Binz, H., Roth, D., "Elaboration and assessment of a set of criteria for the evaluation of product ideas", ICED13, Seoul, Korea, 2013.
Otto, K. and K. Wood (2001). Product Design: Techniques in Reverse Engineering and New Product Development. Upper Saddle River, NJ, Prentice Hall.
Ouellette, M., "Form Verification for the Conceptual Design of Complex Mechanical Systems", MS Thesis, Georgia Institute of Technology, May 1992
Pahl, G. and W. Beitz (1996). Engineering Design: A Systematic Approach. (2nd ed) New York, Springer-Verlag.
Pareto, V. Manuale di Economia Politica. Societa Editric Libraria, Milano, Italy 1906. Translated by Schwier, A. S., as Manual of Political Economy, Macmillian, New York, 1971
Stern, T. and Jaberg, H. (2010) Erfolgreiches Innovationsmanagement. Wiesbaden: Gabler
Stevanovic, M., Marjanovic, D., Storga, M., " A model of Idea Evaluation and Selection for Product Innovation », ICED 15 Volume: DS 80-8, Milan, Italy, 2015
Tzokas, N., Hultink, E. and Hart, S. (2004) Navigating the new product development process. Industrial Marketing Management, Vol. 33, No. 7, pp. 619-626.
von Ahsen, A., Kuchenbuch, A. and Heesen, M. (2010) Leitfaden: Bewertung von Innovationen im Mittelstand. In von Ahsen, A. (ed), Bewertung von Innovationen im Mittelstand, Heidelberg: Springer, pp. 39-74.
Ward, A. (2007). Lean Product and Process Development. LEI. ISBN 978-1934109137.
Wright, P. (2012). The three levels of innovation. CEO Forum
Yannou, B., Jankovic, M., Leroy, Y., Kremer, G. "Observations from radical innovation projects considering the company context". Journal of Mechanical Design, American Society of Mechanical Engineers, 2013, 135 (2), pp.1-21